Program Analysis – Lecture 15

Specification Mining

Prof. Dr. Michael Pradel

Software Lab, University of Stuttgart

Winter 2019/2020

Partly based on slides from Michael Ernst, Andreas Zeller, and Andrzej Wasylkowski

Warm-up Quiz

What does the following JavaScript code print?

```
let x = [1, 2, 1];
let y = [2, 3, 2];
let z;
if (Number.MIN_VALUE > 0) {
    z = x + y;
} else {
    z = x[y.length - 1];
}
console.log(z);
```

https://ilias3.uni-stuttgart.de/vote/KN2I

Warm-up Quiz

What does the following JavaScript code print?

```
let x = [1, 2, 1];
let y = [2, 3, 2];
let z;
if (Number.MIN_VALUE > 0) {
    z = x + y;
} else {
    z = x[y.length - 1];
}
console.log(z);
```

Result: 1,2,12,3,2

https://ilias3.uni-stuttgart.de/vote/KN2I

Warm-up Quiz

What does the following JavaScript code print?

```
let x = [1, 2, 1];
let y = [2, 3, 2];
let z;
if (Number.MIN_VALUE > 0) {
    z = x + y;
} else {
    z = x[y.length - 1];
}
console.log(z);
```

Result: 1,2,12,3,2

`MIN_VALUE`: Smallest *positive* value that can be representated within floating point precision

(Use `NEGATIVE_INFINITY` for the overall smallest value)

https://ilias3.uni-stuttgart.de/vote/KN2I

Warm-up Quiz

What does the following JavaScript code print?

```
let x = [1, 2, 1];
let y = [2, 3, 2];
let z;
if (Number.MIN_VALUE > 0) {
    z = x + y;
} else {
    z = x[y.length - 1];
}
console.log(z);
```

Adding two arrays: Convert both to string and concatenate

Result: 1,2,12,3,2

https://ilias3.uni-stuttgart.de/vote/KN2I

Outline

1. **Introduction**
2. **Program Invariants**
3. **Finite State Machines**
4. **Programming Rules**

Mostly based on these papers:

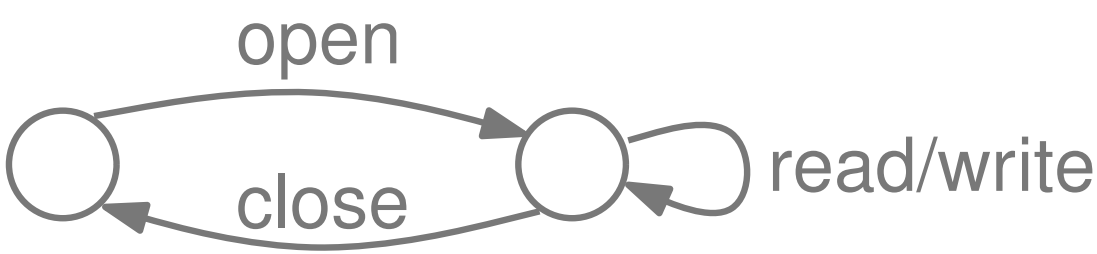
- *Dynamically Discovering Likely Program Invariants to Support Program Evolution* , Ernst et al., IEEE TSE, 2001
- *Mining Specifications*, Ammons et al., POPL, 2002
- *PR-Miner: Automatically Extracting Implicit Programming Rules and Detecting Violations in Large Software Code*, Li & Zhou, FSE 2005

Formal Specifications

- Formal, **mathematical** description of the **intended behavior** of a program
- Examples:
  - Pre- and post-conditions:

```
// pre: typeof(x) === "number"
function abs(x) { ... }
// post: typeof(ret) === "number" &&
//       ret >= 0
```

  - Finite-state machines:



Uses of Specifications

Traditionally, mainly used for formal verification

- Demonstrate that program is correct w.r.t. its specification
- Mathematical proof
- Ideally, static verification
  - Avoid running an incorrect program
- Also: Runtime verification
  - Detect and potentially prevent problems when they occur

The Problem

So why not formally specify and verify all software?

- Huge effort
- Completely specifying a large system is practically impossible
- Complex specification is likely to have mistakes
- In practice:
  - Used mostly for safetly critical systems
  - Used only to specify important properties (e.g., no crash)

Specification Mining

- Idea: Infer specifications from existing software
  - No human effort
  - Get specifications ”for free”
- Examples:
  - Pre- and post-conditions:
    Analyze function and check which properties the inputs and outputs fulfill
  - Finite state machines:
    Analyze code and identify its states and transitions between them

Wait a Minute ...

- How to validate that a program is correct by inferring the specification from the program itself?
- Sounds contradictory, but it works
  - Infer common behavior, report anomalies as potential bugs
  - Infer specifications from one code base, use them to check another
    - Different programs that use the same API
    - Different versions of the same program
  - Detect inconsistencies in the code itself (non-null assumption vs. null check)

Uses of Mined Specifications

- **Software evolution**
  - Understand behavior of program
  - Generate documentation
  - Use as oracle for regression testing
- **Anomaly detection**
  - Outliers are potential bugs
- **Support formal specification of an existing system**
  - Starting point for full specification

Outline

1. **Introduction**
2. **Program Invariants** ←
3. **Finite State Machines**
4. **Programming Rules**

Mostly based on these papers:

- *Dynamically Discovering Likely Program Invariants to Support Program Evolution* , Ernst et al., IEEE TSE, 2001
- *Mining Specifications*, Ammons et al., POPL, 2002
- *PR-Miner: Automatically Extracting Implicit Programming Rules and Detecting Violations in Large Software Code*, Li & Zhou, FSE 2005

Program Invariants

- Invariant = Data property that holds in all runs
  - At entry of f(), x is an odd number
  - $0 \leq y \leq 10$
- Useful in software development
  - Protect programmers from making erroneous changes
  - Verify properties of a program
- Can be explicitly stated in programs
  - Programmers can annotate code with invariants
  - Huge effort
  - Important invariants may be missed

Example

```
function sumArray(b, n) {
  var i = 0, s = 0;
  while (i !== n) {
    s += b[i];
    i++;
  }
  return s;
}
```

Example

Some invariants from running with 100 randomly generated inputs of length 7-13:

```
function sumArray(b, n) {
  var i = 0, s = 0;
  while (i !== n) {
    s += b[i];
    i++;
  }
  return s;
}
```

- Pre-conditions:
  - $n = b.length$
  - $7 \leq n \leq 13$
- Post-conditions:
  - $n = i = b.length$
  - $b = orig(b)$
  - $s = sum(b)$
- Loop invariants
  - $n = b.length$
  - $0 \leq i \leq 13$
  - $s = sum(b[0..i-1])$

Daikon Invariant Detector

- **Dynamic analysis: Infers invariants from particular execution**
- **Step 1: Instrument source code**
  - Trace variables of interest
- **Step 2: Run instrumented program using test suite**
- **Step 3: Infer invariants from instrumented and derived variables**

Step 1: Instrumentation

Insert instrumentation points

- Function entry
- Function exit
- Loop heads

Write to a file values for

- all variables in scope
- global variables
- function arguments
- local variables
- function's return value

Step 2: Execution

- **Instrumented program writes file with runtime values**
- **Result: Trace of execution**

Step 3: Inference

Daikon has library of invariant patterns over variables (e.g., x, y, z) and constants (e.g., a, b, c), e.g.:

- Check for each variable:
  - Constant or small number of values
- Check for numeric variables:
  - Range: $a \leq x \leq b$
- Check for multiple numbers:
  - Set of functions, e.g., $x = abs(y)$
  - Comparisons, e.g., $x < y$
- Check for sequences:
  - Sortedness

Step 3: Inference

Daikon has library of invariant patterns over variables (e.g., x, y, z) and constants (e.g., a, b, c), e.g.:

- Check for each variable:
  - Constant or small number of values
- Check for numeric variables:
  - Range: $a \leq x \leq b$
- Check for multiple numbers:
  - Set of functions, e.g., $x = abs(y)$
  - Comparisons, e.g., $x < y$
- Check for sequences:
  - Sortedness

Only matching patterns are preserved

Quiz

What post-conditions could Daikon infer from tests `g(1)` and `g(3)`?

```
function g(n) {
  var x = n * 2;
  var y = 0;
  for (var i = 0; i < x; i++) {
    y += i;
  }
  return y;
}
```

$x < y$ $\quad$ $i \geq 2$ $\quad$ $1 \leq y \leq 15$ $\quad$ $n = 1$

Quiz

What post-conditions could Daikon infer from tests `g(1)` and `g(3)`?

```
function g(n) {
  var x = n * 2;
  var y = 0;
  for (var i = 0; i < x; i++) {
    y += i;
  }
  return y;
}
```

$x < y$

$i \geq 2 \qquad 1 \leq y \leq 15$

$n = 1$

Outline

1. **Introduction**
2. **Program Invariants**
3. **Finite State Machines** ←
4. **Programming Rules**

Mostly based on these papers:

- *Dynamically Discovering Likely Program Invariants to Support Program Evolution* , Ernst et al., IEEE TSE, 2001
- *Mining Specifications*, Ammons et al., POPL, 2002
- *PR-Miner: Automatically Extracting Implicit Programming Rules and Detecting Violations in Large Software Code*, Li & Zhou, FSE 2005

Example: Socket API

```
int s = socket(AF_INET, SOCK_STREAM, 0);
bind(s, &serv_addr, sizeof(serv_addr));
listen(s, 5);
while (true) {
  int ns = accept(s, &addr, &len);
  if (ns < 0) break;
  do {
    read(ns, buffer, 255);
    write(ns, buffer, size);
    if (cond1) return;
  } while (cond2)
  close(ns);
}
close(s);
```

Automata Mining

- Many APIs impose usage protocols on its clients
  - Not formally specified, but implicit in implementation/documentation
- Idea: Dynamically analyze API usage of clients and infer protocols
  - Assumption: Most API usages are correct
- Approach:
  - Instrument and execute program $\rightarrow$ Trace
  - Extract scenarios = small sequences of dependent API calls
  - Learn finite state machine

Execution Trace

```
socket(domain = 2, type = 1, proto = 0, return = 7)
bind(so = 7, addr = 0x400120, addr_len = 6, return = 0)
listen(so = 7, backlog = 5, return = 0)
accept(so = 7, addr = 0x400200, addr_len = 0x400240,
return = 8)
read(fd = 8, buf = 0x400320, len = 255, return = 12)
write(fd = 8, buf = 0x400320, len = 12, return = 12)
read(fd = 8, buf = 0x400320, len = 255, return = 7)
write(fd = 8, buf = 0x400320, len = 7, return = 7)
close(fd = 8, return = 0)
accept(so = 7, addr = 0x400200, addr_len = 0x400240,
return = 10)
read(fd = 10, buf = 0x400320, len = 255, return = 13)
write(fd = 10, buf = 0x400320, len = 13, return = 13)
close(fd = 10, return = 0)
close(so = 7, return = 0)
```

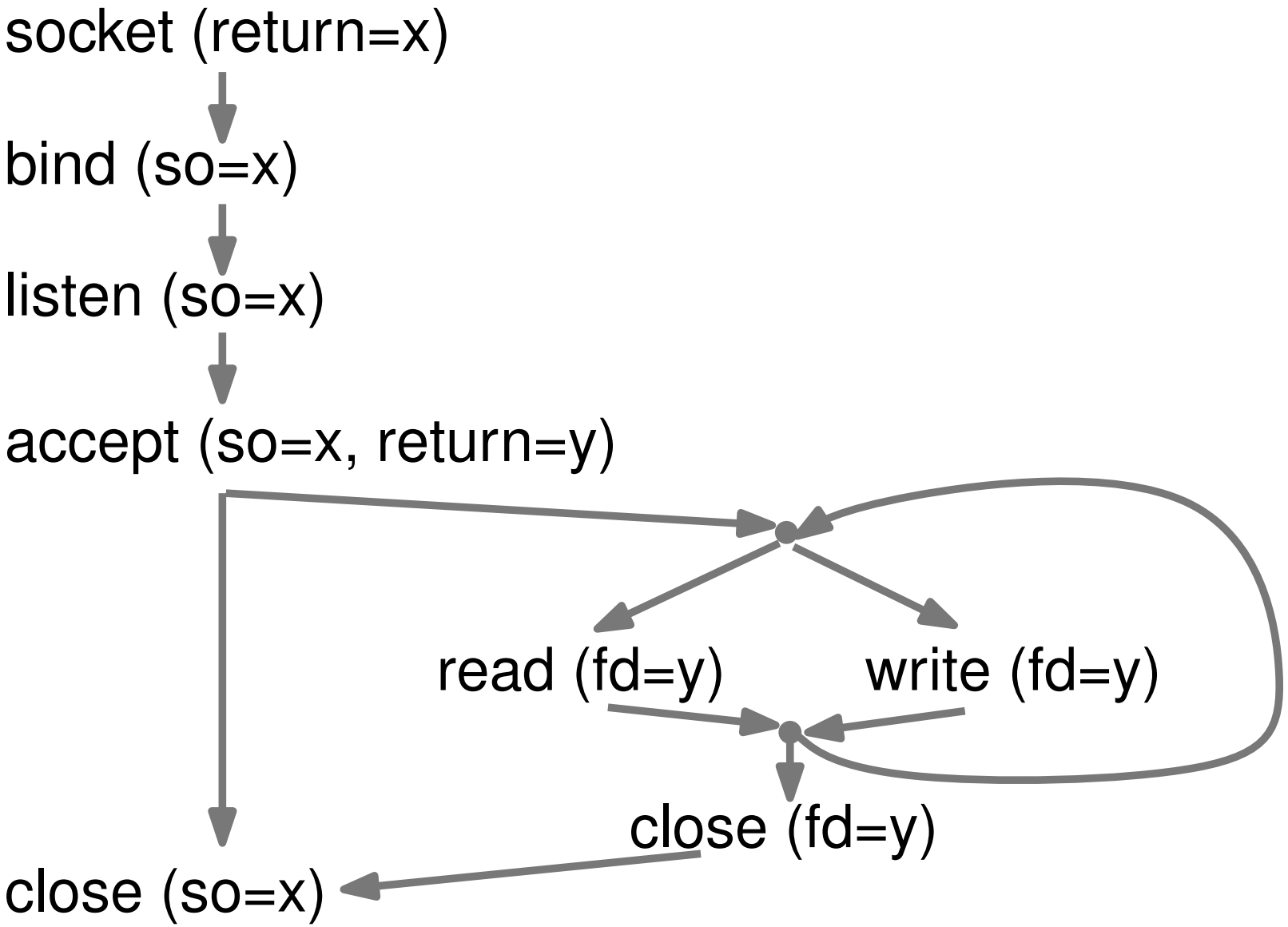
Execution Trace

socket(domain = 2, type = 1, proto = 0, return = 7)
bind(so = 7, addr = 0x400120, addr_len = 6, return = 0)
listen(so = 7, backlog = 5, return = 0)
accept(so = 7, addr = 0x400200, addr_len = 0x400240, return = 8)
read(fd = 8, buf = 0x400320, len = 255, return = 12)
write(fd = 8, buf = 0x400320, len = 12, return = 12)
read(fd = 8, buf = 0x400320, len = 255, return = 7)
write(fd = 8, buf = 0x400320, len = 7, return = 7)
close(fd = 8, return = 0)
accept(so = 7, addr = 0x400200, addr_len = 0x400240, return = 10)
read(fd = 10, buf = 0x400320, len = 255, return = 13)
write(fd = 10, buf = 0x400320, len = 13, return = 13)
close(fd = 10, return = 0)
close(so = 7, return = 0)

Execution Trace

socket(domain = 2, type = 1, proto = 0, return = 7)
bind(so = 7, addr = 0x400120, addr_len = 6, return = 0)
listen(so = 7, backlog = 5, return = 0)
accept(so = 7, addr = 0x400200, addr_len = 0x400240,
return = 8)
read(fd = 8, buf = 0x400320, len = 255, return = 12)
write(fd = 8, buf = 0x400320, len = 12, return = 12)
read(fd = 8, buf = 0x400320, len = 255, return = 7)
write(fd = 8, buf = 0x400320, len = 7, return = 7)
close(fd = 8, return = 0)
accept(so = 7, addr = 0x400200, addr_len = 0x400240,
return = 10)
read(fd = 10, buf = 0x400320, len = 255, return = 13)
write(fd = 10, buf = 0x400320, len = 13, return = 13)
close(fd = 10, return = 0)
close(so = 7, return = 0)

Inferred Specification



Outline

1. **Introduction**
2. **Program Invariants**
3. **Finite State Machines**
4. **Programming Rules** ←

Mostly based on these papers:

- *Dynamically Discovering Likely Program Invariants to Support Program Evolution* , Ernst et al., IEEE TSE, 2001
- *Mining Specifications*, Ammons et al., POPL, 2002
- *PR-Miner: Automatically Extracting Implicit Programming Rules and Detecting Violations in Large Software Code*, Li & Zhou, FSE 2005

PR-Miner

- Static specification mining technique
- Idea: Find implicit programming rules and warn about paths where rules are violated
  - E.g., using one variable/function implies using another
- Main steps:
  - Extract symbols names from each function
  - Use frequent itemset mining to identify symbols that often occur together $\rightarrow$ Programming rules
  - Search paths where one symbol is used but not another $\rightarrow$ Violations of rules

Example

```
// function source code
getRelationDescription (...) {
  HeapTuple relTup;
  ...
  relTup = SearchSysCache (...);
  if (!HeapTupleIsValid(relTup))
    elog (...);
  relForm = ...;
  ...
  ReleaseSysCache (relTup);
}
```

Example

```
// function source code
getRelationDescription (...) {
  HeapTuple relTup;
  ...
  relTup = SearchSysCache (...);
  if (!HeapTupleIsValid(relTup))
    elog (...);
  relForm = ...;
  ...
  ReleaseSysCache (relTup);
}
```

Itemset:

HeapTuple

SearchSysCache

HeapTupleIsValid

elog

ReleaseSysCache

...

Example (2)

More itemsets:

HeapTuple	StringInfoData	Form_pg_class
SearchSysCache	getObjectClass	SearchSysCache
HeapTupleIsValid	HeapTuple	elog
elog	SearchSysCache	RelationIsVisible
ReleaseSysCache	NameStr	ReleaseSysCache
...	Relation	...
	ReleaseSysCache	
	...	

Example (2)

More itemsets:

HeapTuple	StringInfoData	Form_pg_class
SearchSysCache	getObjectClass	SearchSysCache
HeapTupleIsValid	HeapTuple	elog
elog	SearchSysCache	RelationIsVisible
ReleaseSysCache	NameStr	ReleaseSysCache
...	Relation	...
	ReleaseSysCache	
	...	

- Frequent itemset:
  SearchSysCache, ReleaseSysCache
- Missing items point to potential bugs

Summary

- Specification mining:
  Extract formal specification from existing program
  - Often builds on data mining techniques
- Useful for bug detection, program understanding, documentation, etc.
- Main challenge: Keep false positive warnings at reasonable level
- Active research topic with many interesting, open questions